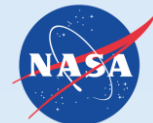# Model-Based Engine Control: Potential Impacts on Engine Design

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Model-Based Engine Control Overview

- Model-Based Engine Control (MBEC) is a method of using an on-board model to estimate the desired control parameters, such as thrust and stall margin

- MBEC Concept has been around since the early 1990s
  - The challenge has been model accuracy over the engine life cycle
  - The approach here is to apply an Optimal Tuner Kalman Filter (OTKF) to serve as the on-board model

- MBEC is being developed as one of the advanced engine control system methodologies to improve turbofan engine performance, safety, and efficiency.

CMAPSS40k Traditional Control Systems
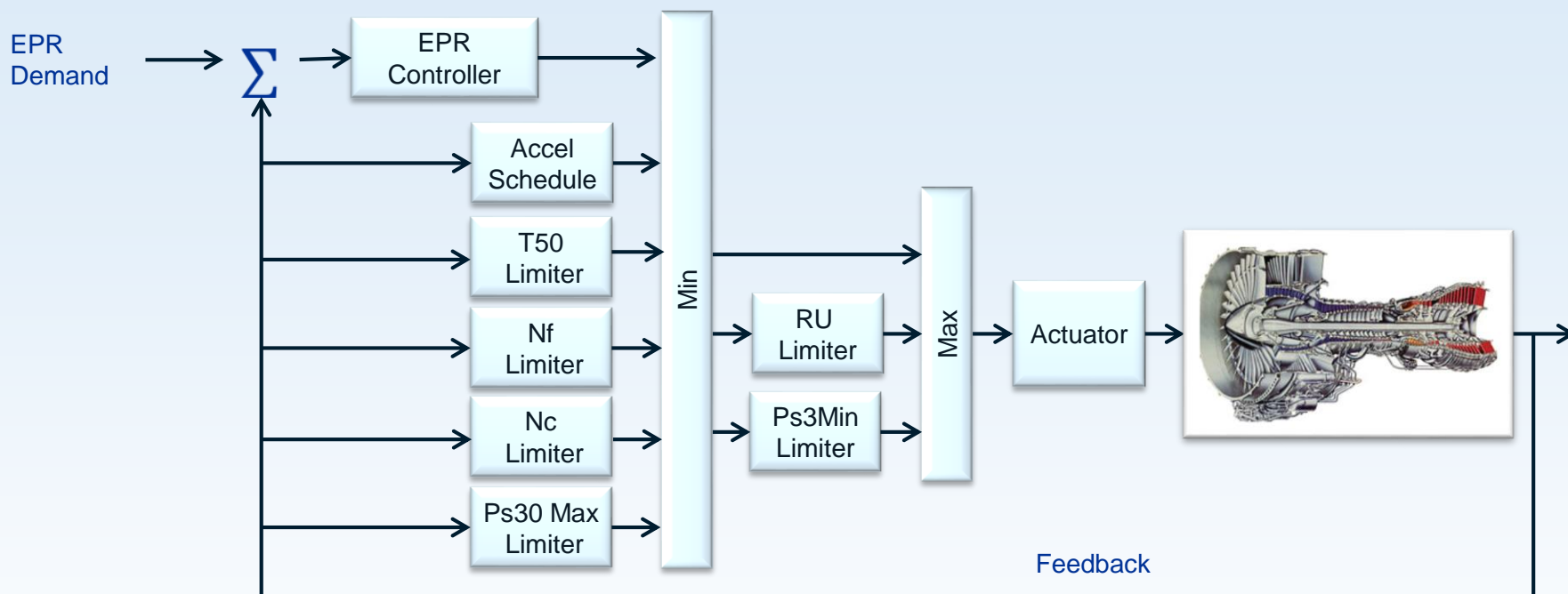
- Thrust cannot be measured and hence is indirectly controlled through regulating a measured variable which correlates with thrust e.g., Fan Speed, Engine Pressure Ration (EPR).

- Stall Margins (SM) cannot be measured. Safe margins are indirectly maintained by acceleration and deceleration limits.

MBEC Applied to CMAPSS40k
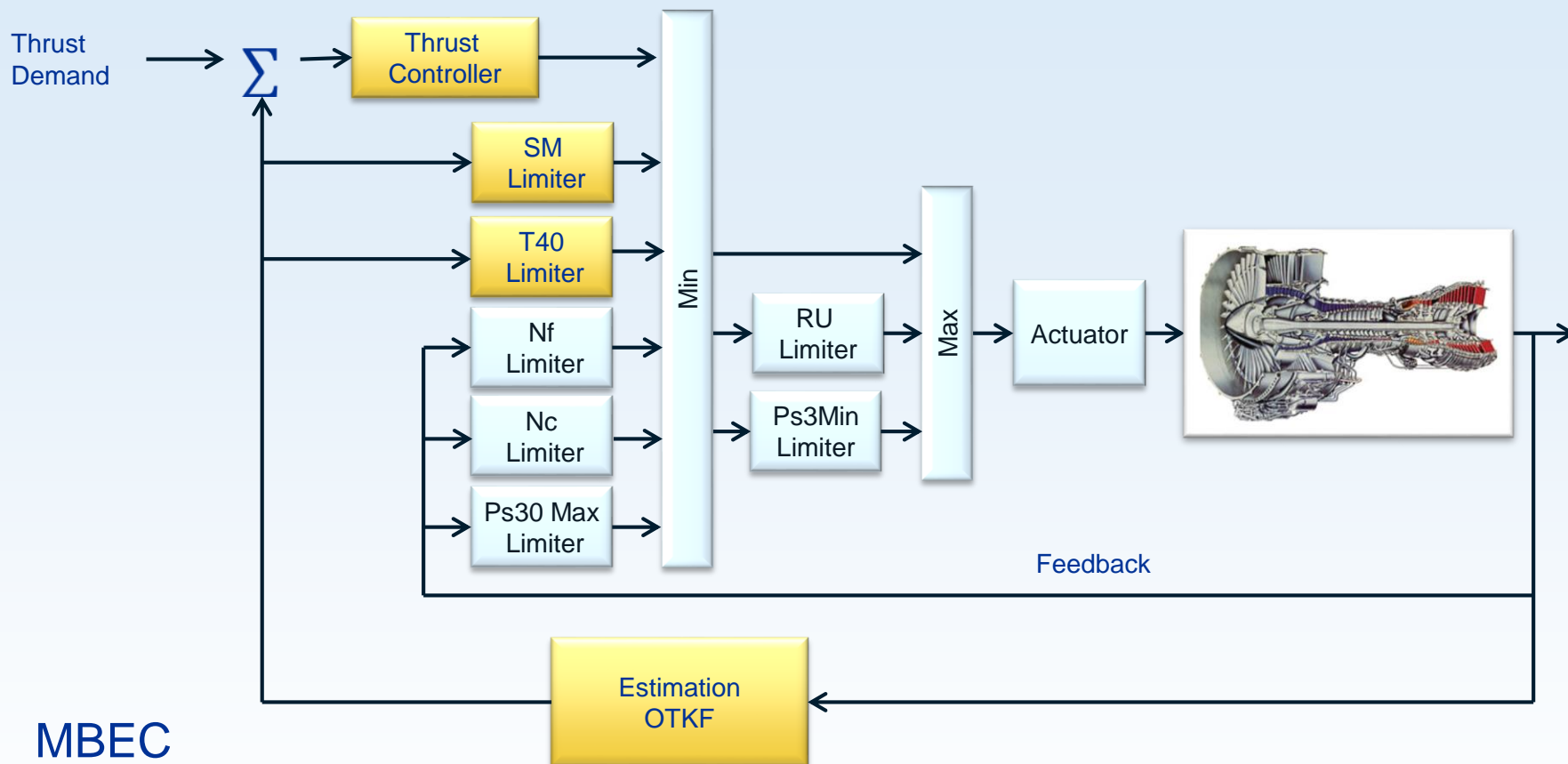
- # MBEC
  - Thrust Estimate Main Control replaced EPR
- # Nominal operating line is conservative to maintain life cycle safety margins.
- # SM Limiter replaces Acceleration Limiter and T40 Limiter helps to maintain safety while changing engine controlled response
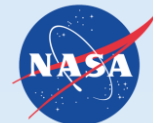
Exploring the Benefits of MBEC

- The primary benefit of MBEC is to provide accurate estimates of key unmeasured safety parameters such as SM and combustor exit temperature (T40)
  – This accurate estimation can be used to reduce conservative safety margins in a trade for performance and/or efficiency

- During an emergency situation MBEC can be used to improve the dynamic response time of the engine
  – This is accomplished by reducing the HPC SM threshold to an acceptable level, while still monitoring T40
  – Investigating extended Kalman Filter to improve transient estimation

- **MBEC can be used during the design phase to improve efficiency through iterations with engine designers to set the operating line by modifying SM stack up margin**
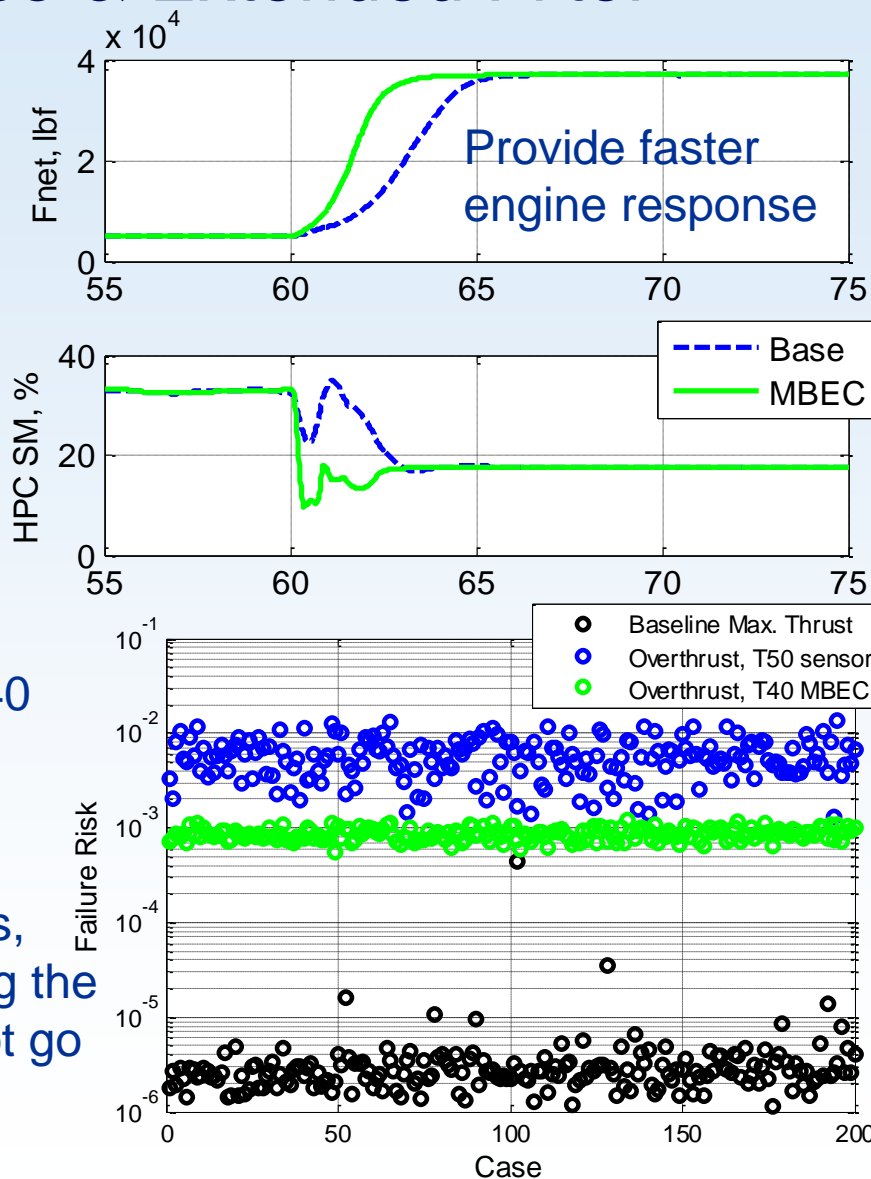
MBEC: Enhanced Response & Extended Filter

- The OTKF and OTEKF are tested at 100 random takeoff conditions
- Results show the maximum absolute error for three engine parameters during transient operation.

Provide faster engine response
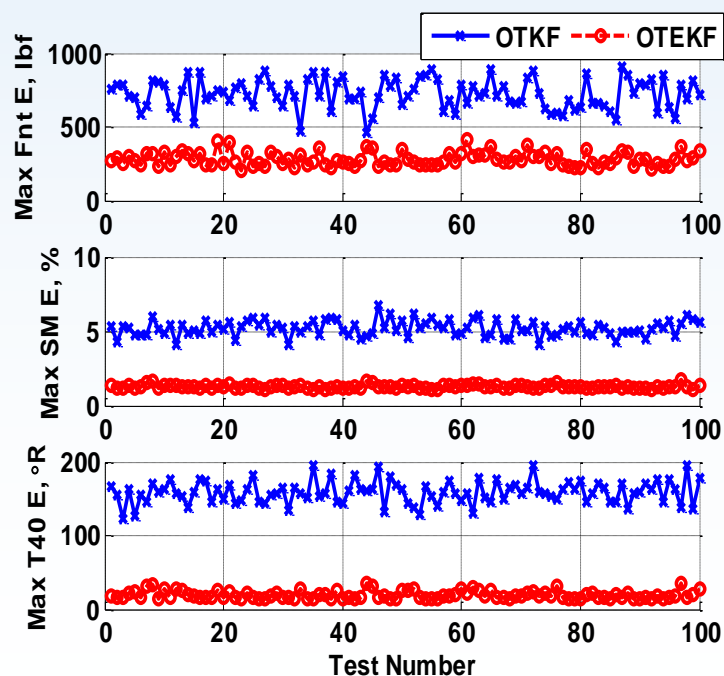
Estimating T40 could provide similar performance improvements, while ensuring the engine will not go into stall

Baseline Estimation Results

- The baseline estimation is conducted about the cruise condition consisting of 100 distinct operating conditions spanning the engine life cycle.

- At each condition a step up and down in PLA is conducted to obtain multiple steady-state conditions and the transient response
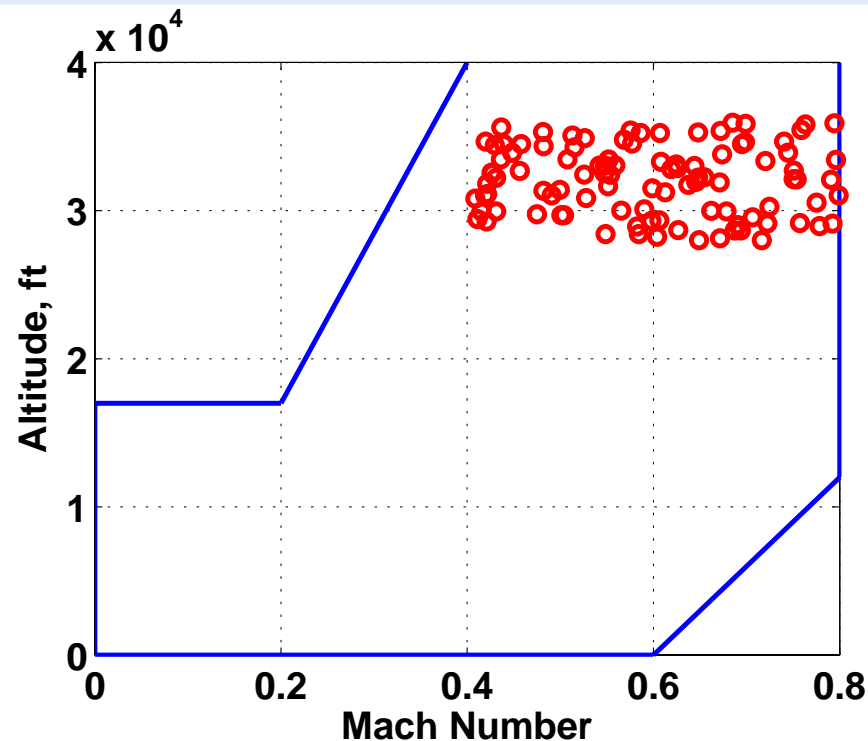
Steady-State Estimation

- During each simulation three steady-state points exist,
  - The maximum percent difference is plotted

- It is shown that during steady-state at cruise the estimation is very accurate
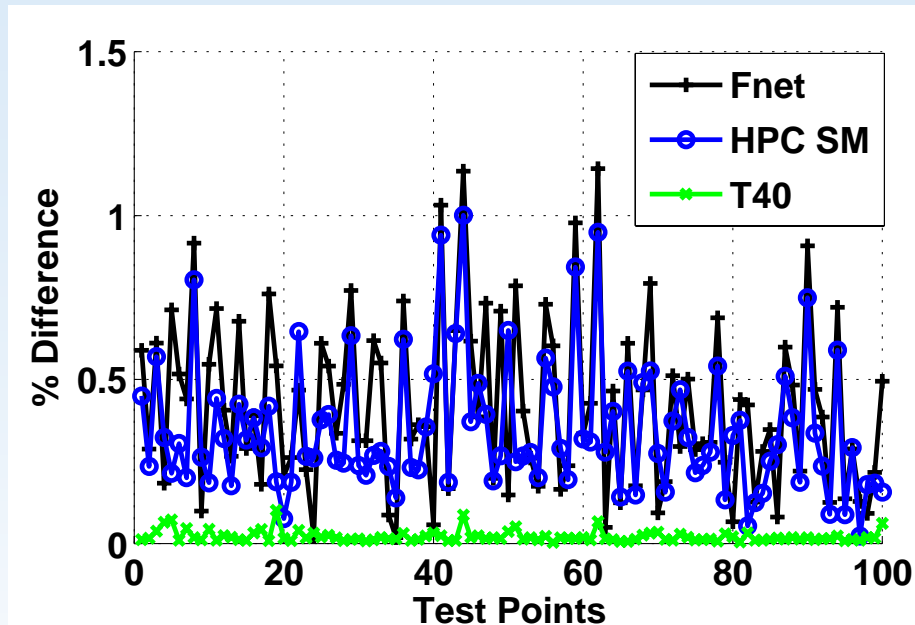
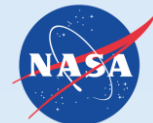| Parameter	Max % Difference
Net Thrust	1.14
HPC Stall Margin	1.03
T40	0.10

Unsteady Estimation

- The maximum % difference is plotted for each test point during the PLA change

  – The errors during the transient increase, but still remain less than 10% in the worst case

- The critical information is the HPC SM for redesigning the performance maps
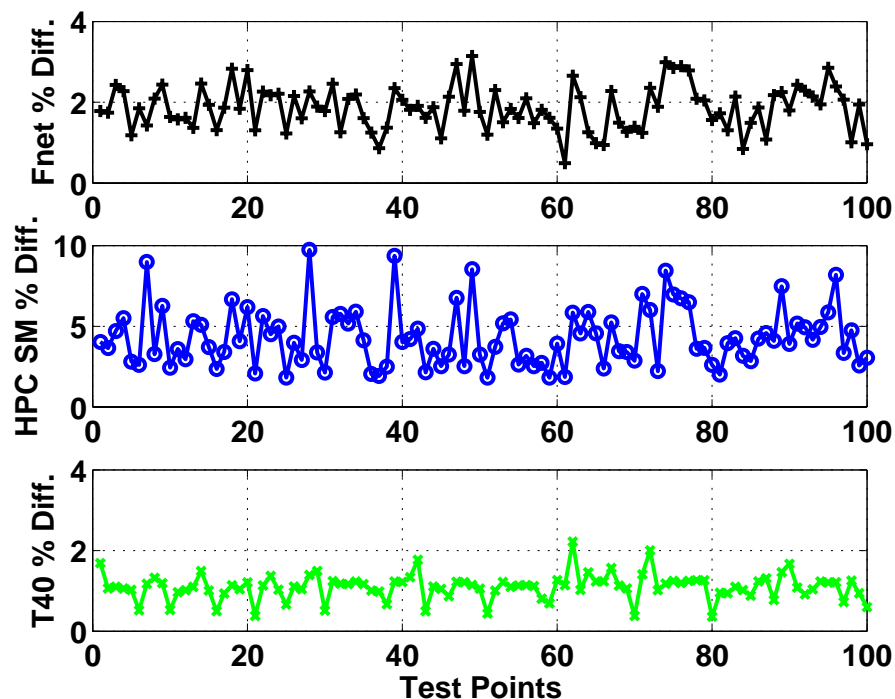
| Parameter	Max % Difference
Net Thrust	3.15
HPC Stall Margin	9.74
T40	2.22

Performance Map Design

- Once a commercial engine is designed the available actuators do not allow for significantly altering the operating point on a given performance map.
  - The benefits shown here for scaling the map are assumed to be considered in an early design phase
  - A wider range of the compressor performance map can be used for operation due to reduced margins while using MBEC estimated parameters to maintain safety

- A simple scaling of the LPT and HPT performance maps was conducted to reduce the expected corrected mass flow to 97.5% of nominal.
  - This is done to illustrate the potential added flexibility and efficiency gains provided to an engine designer if controls are considered during the design phase

# Steady-State T40 and HPC Stall Margin

- ## Initial testing done with the linear solver

  - Test points are at the same operating condition, using a PLA sweep from 58-78 degrees
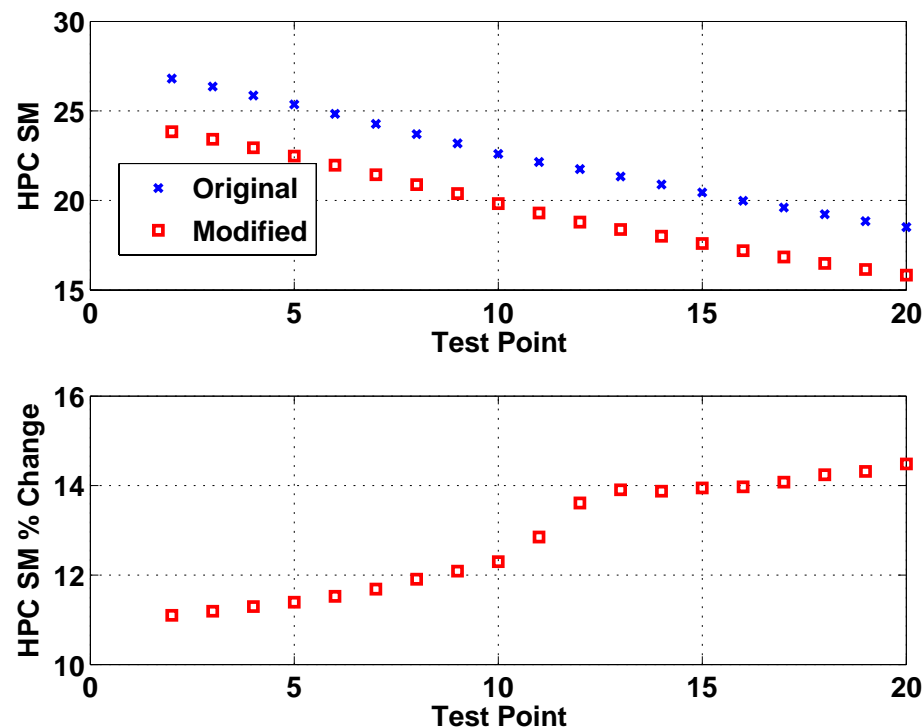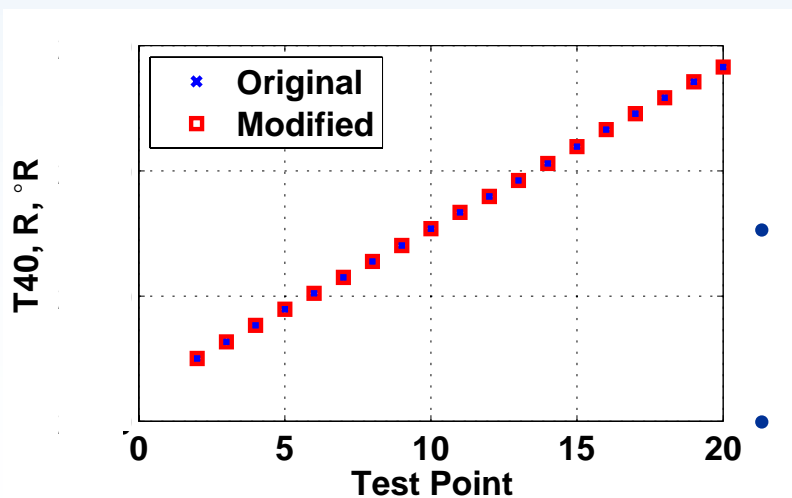
- For the following results the blue data is the original CMAPSS40k and red is the results given the modified performance maps
- T40 is clearly held constant, while the HPC SM has a percent change of about 10-15%

LPC and HPC Performance Maps

- The original operating line is plotted in blue and the modified design is in green.
  - It is clearly shown here that the turbine scaling results in a shift of the operating line towards the yellow stall line
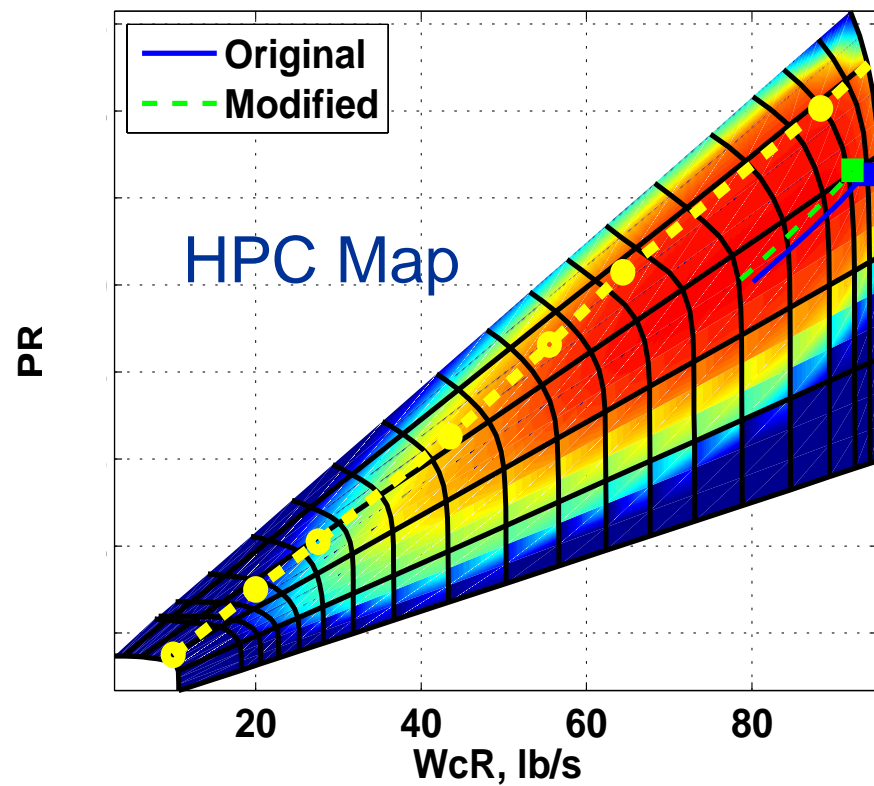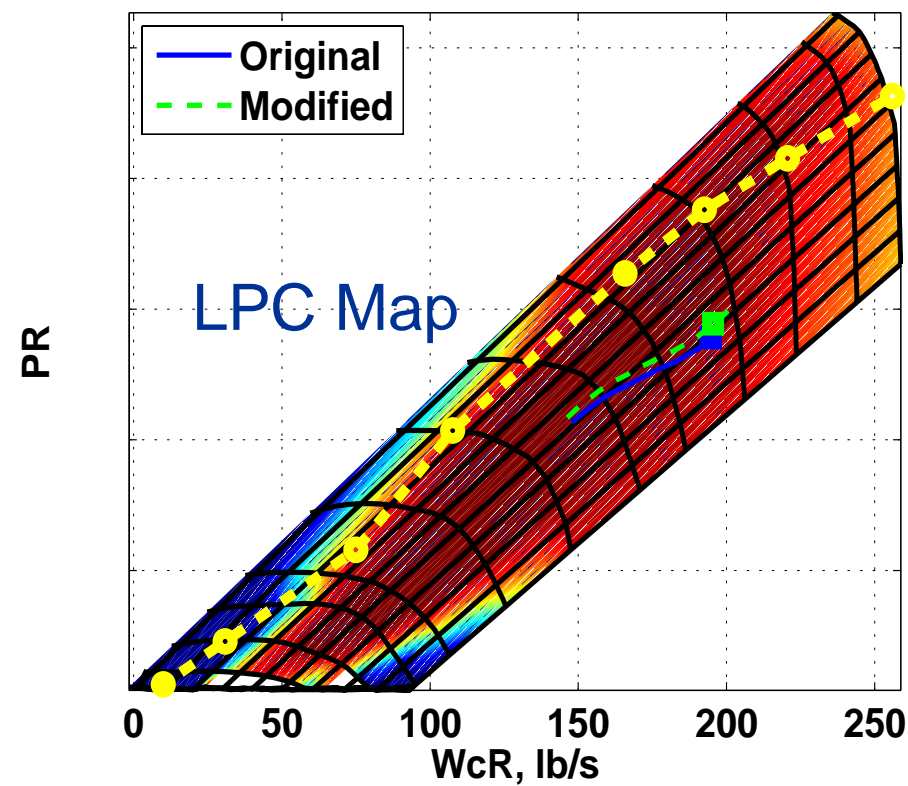
HPT and LPT Performance Maps

- The original operating line is plotted in blue and the modified design is in green.
    - Here the turbine is operating in a choked or near choked condition and the operating region is small
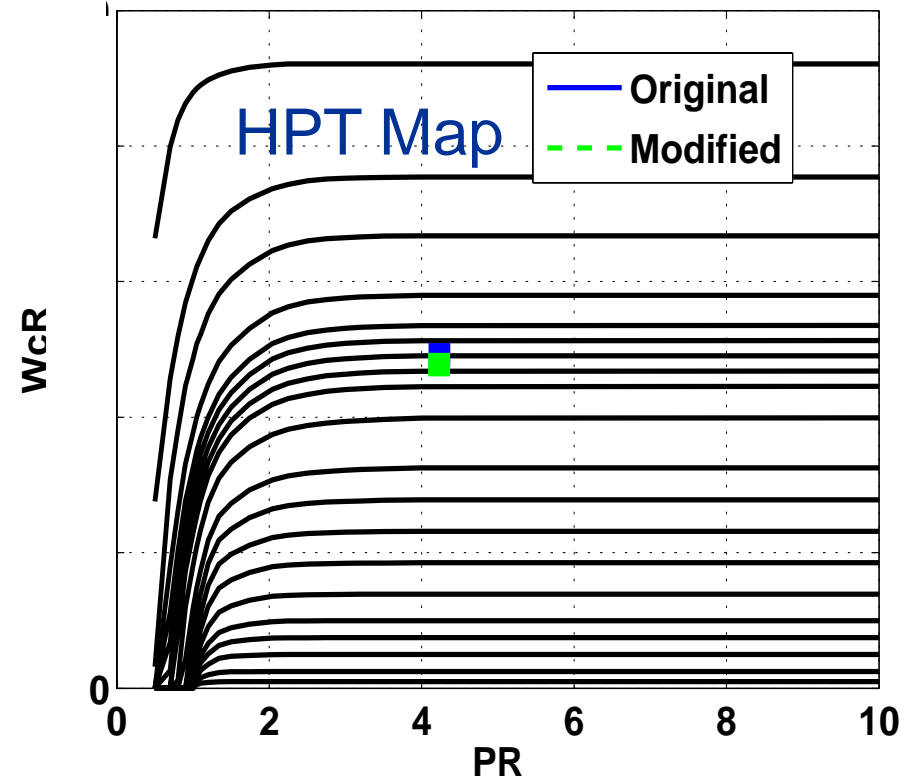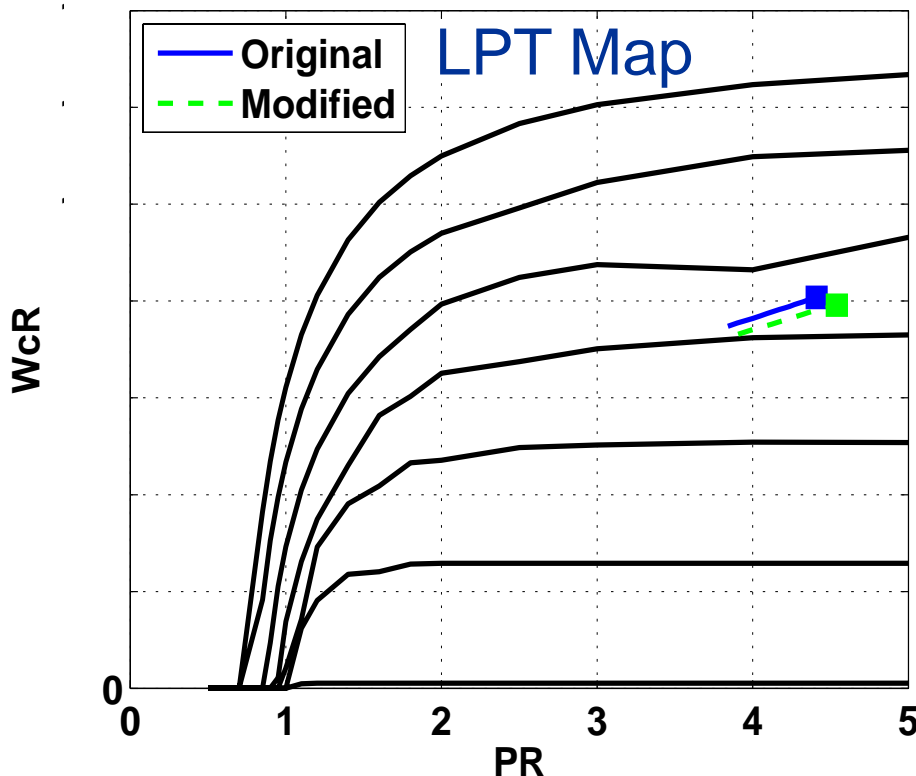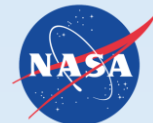
MBEC Design for Efficiency Improvements

- A new piece-wise linear model is developed based on the scaled performance maps

- An optimal tuner Kalman filter is designed for the new linear model

- The thrust output from a previous EPR run at the 100 cruise points is used as the thrust demanded for the MBEC thrust controller.
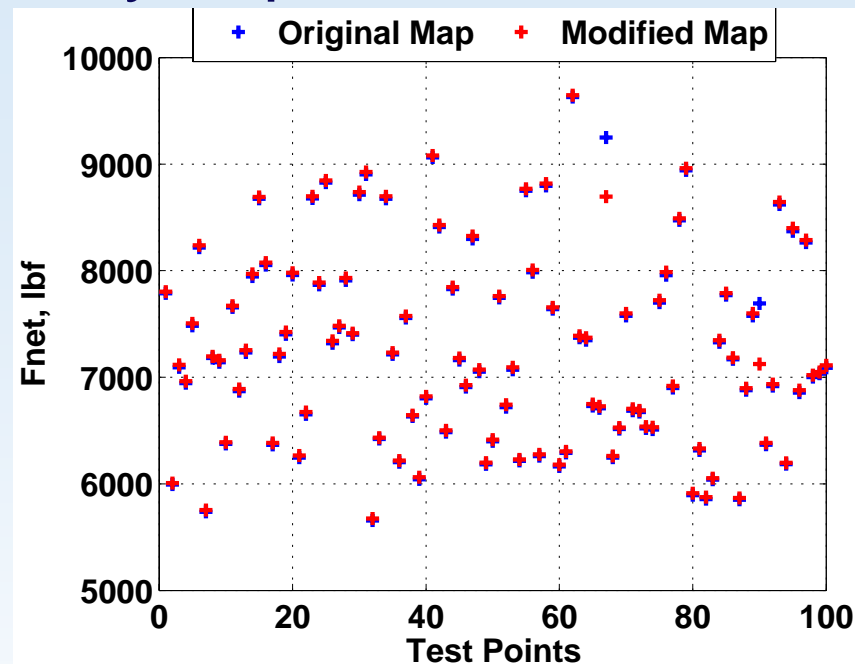

The Fnet generated from the baseline map and EPR controller closely matches that of the MBEC architecture with the modified maps
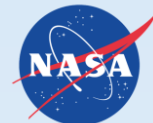
MBEC HPC Stall Margin Limiter

- To ensure that the HPC SM is not violated a new limiter is design to replace the Nc acceleration limiter

- A threshold of 12 HPC SM is set as the red dashed line

- It can be seen that the modified map operates at a lower HPC SM, but the limiter allows for confidence that a defined level of safety is maintained
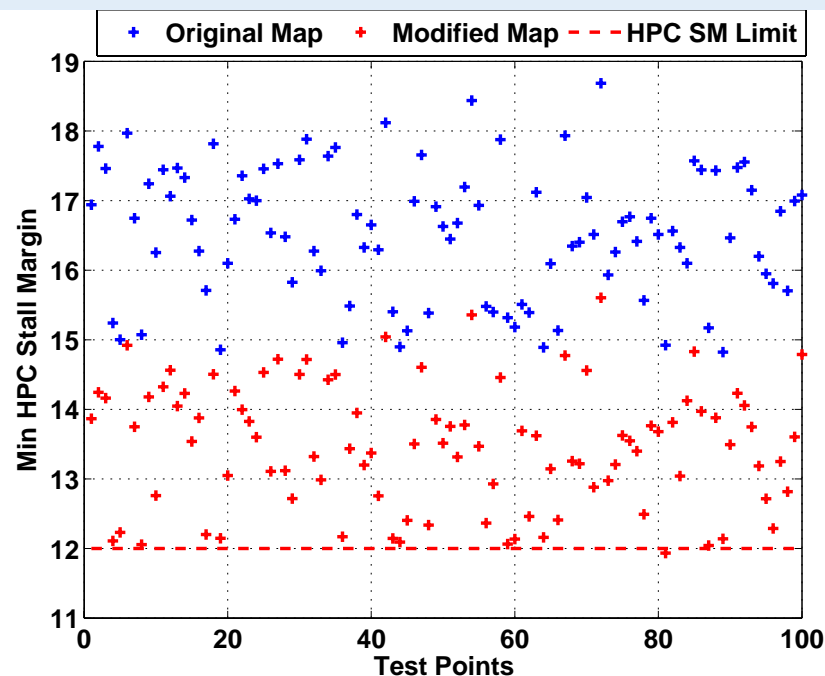
MBEC TSFC Results

- Finally, the full simulation is used to obtain the TSFC improvements

- The full MBEC test with estimation errors, noise, and various deterioration still provides an average of 0.6% reduction in TSFC

  – Initial tests with the steady state linear solver obtained a 1% improvement

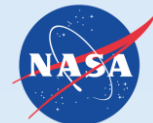 – Deviations from this could be due to changes in Fnet
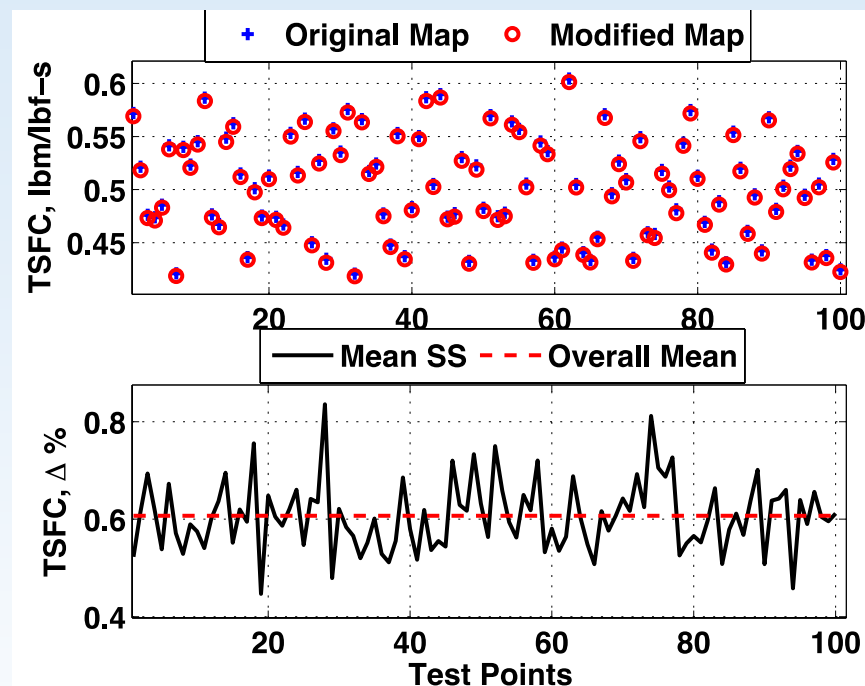
TSFC generated from the baseline map and EPR controller compared to the MBEC architecture with the modified maps, and % improvement of TSFC

Future Work & Conclusions

- Preliminary studies have shown some clear benefits for further developing MBEC:
  - Working with engine system analysis experts to better understand how this work can impact the NPSS design cycle for further improvements and automate the current iterative process
  - Studies show MBEC can improve thrust response and using an Extended Kalman Filters can reduce the larger errors during transients

- This work has illustrated how advance controls can impact the engine design phase, and with modest changes to the operating line can provide some reduction in TSFC during steady-state cruise operation

References

- Csank, J., Connolly, J., "Enhanced Engine Performance During Emergency Operation Using a Model-Based Engine Control Architecture" AIAA 2015-3991

- Connolly, J., Csank, J., Chicatelli, A., Kilver, J., "Model-Based Control of a Nonlinear Aircraft Engine Simulation using an Optimal Tuner Kalman Filter" AIAA 2013-4002

- Connolly, J., Chicatelli, A., Garg, S., "Model-Based Control of an Aircraft Engine using an Optimal Tuner Approach" AIAA 2012-4257

- Future Publication:
  - Csank, J., Connolly, J., "Model-Based Engine Control Architecture with an Extended Kalman Filter"

Questions?